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Geomorphic Framework & Role of Debris Flows

Suspended-Sediment Transport and Sandbars

Glen Canyon Dam Operations – *Post-EIS Summary*

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US Geological Survey - Grand Canyon Monitoring and Research Center

Knowledge Assessment Synthesis II

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Phoenix, AZ

U.S. Department of the Interior
U.S. Geological Survey

Objective of Talk

To summarize knowledge about the geomorpholoy of the Colorado River as it pertains to operations of Glen Canyon Dam & sandbars and sand transport – setup Gram's talk

Take Home Points

- ***Tributary Debris Flows*** ***- control flow and sandbar deposition throughout Marble & Grand Canyons***
- ***Coarse-Grained Sediment*** ***- plays large role in sediment mass balance of the river & ecosystem function***
- ***Dam Operations*** ***– all flow and QW changes in the post-dam era (including ROD) favor export rather than retention of suspended-sand downstream*** **(old & new)**

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Presentation Outline

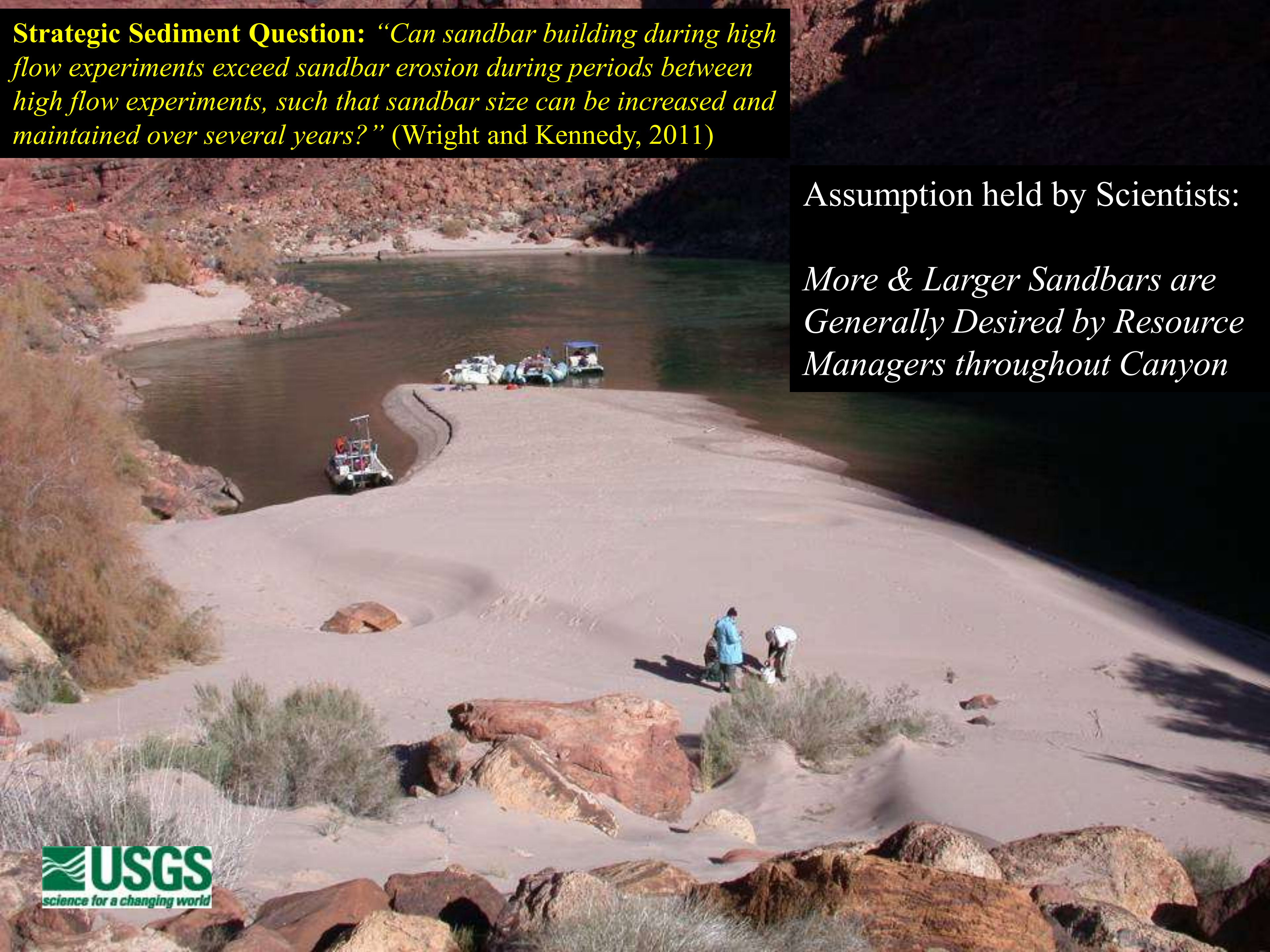
I – Geomorphic Controls - flow & sandbars in Canyon

II- Sediment Mass Balance – two competing sediment budgets – but only one Canyon river

III - GCD & flow of the Colorado River? – the many challenges to sand conservation in the Canyon …

Highlights from: USGS Professional Paper 2003-1677 (Topping et al., 2003)

Strategic Sediment Question: *"Can sandbar building during high flow experiments exceed sandbar erosion during periods between high flow experiments, such that sandbar size can be increased and maintained over several years?"* (Wright and Kennedy, 2011)



Assumption held by Scientists:

More & Larger Sandbars are Generally Desired by Resource Managers throughout Canyon

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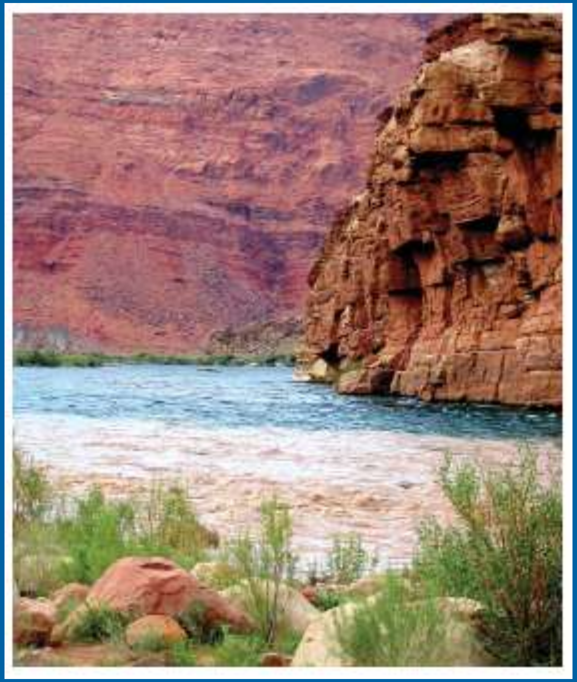
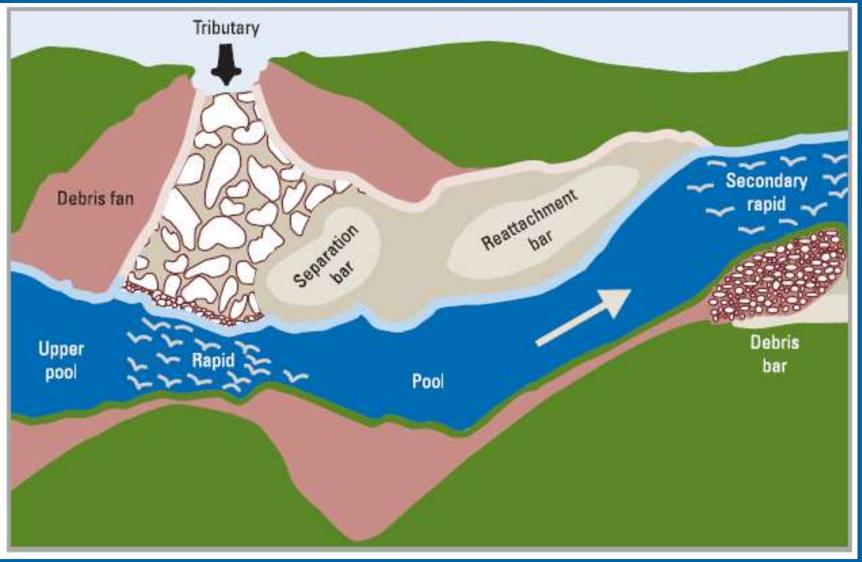
Presentation Outline

I - <u>Geomorphic Controls</u> - flow & sandbars in Canyon



Paria River Sand Supply



Debris-Fan/Eddy Complex

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The Riverine Landscape As Humans Typically Perceive It

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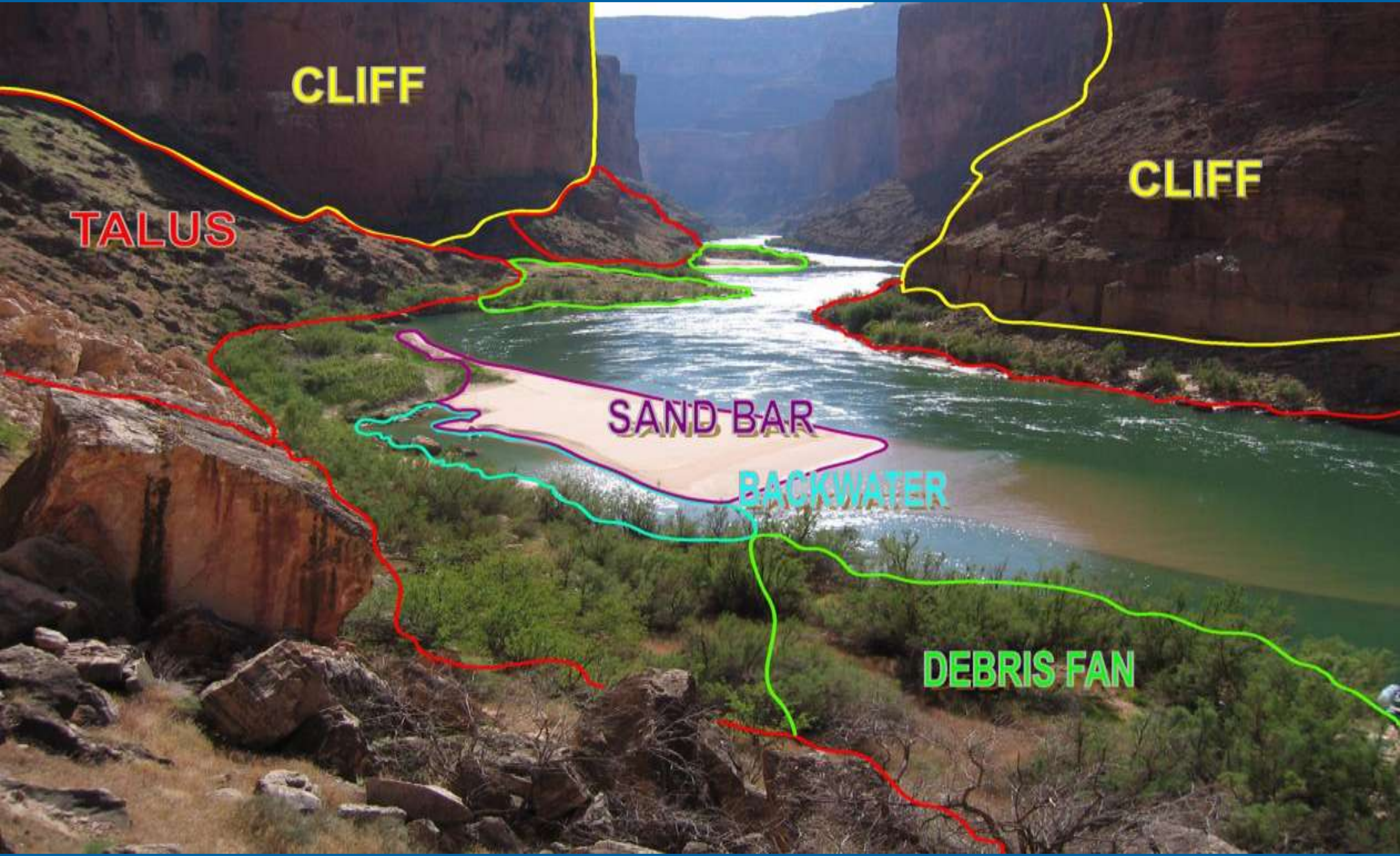
Sand-Filled Eddy – Surrounded by a Sediment-Starved River

Flow in River Continually Contracts & Expands – But Why?



Sandbars are Dynamic & Unstable, but Piles of Boulders Are Not and Persist Under Widely Ranging Flows

Geomorphic Framework for Sandbar Conservation in Grand Canyon

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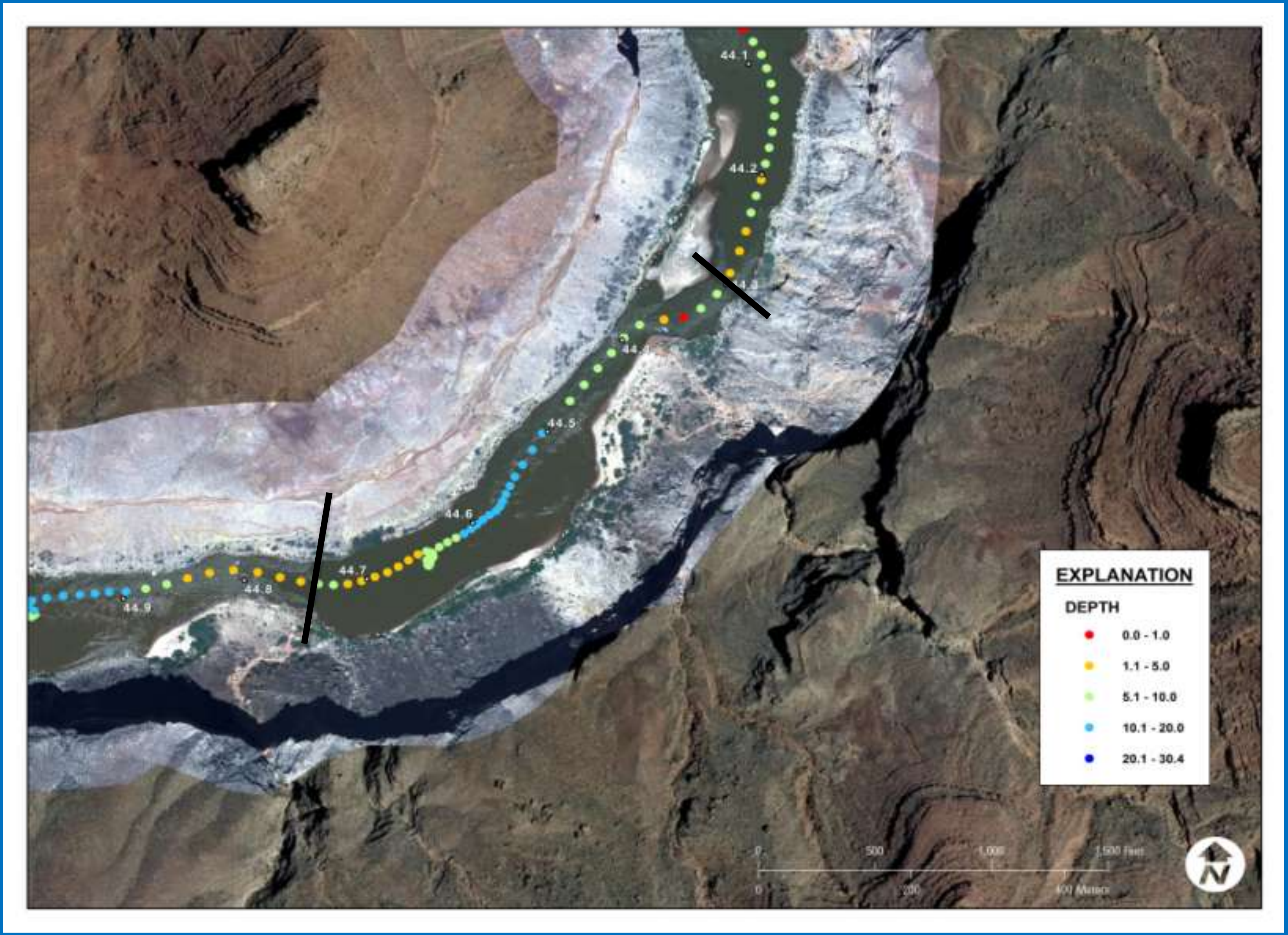
Photo: T. Gushue

<u>Debris Fans</u> – (maintained by Tributary Debris Flows) create "slow-flow" zones where sandbars can reside

Another "Two-Dimensional" Perspective – The "Birds Eye" View



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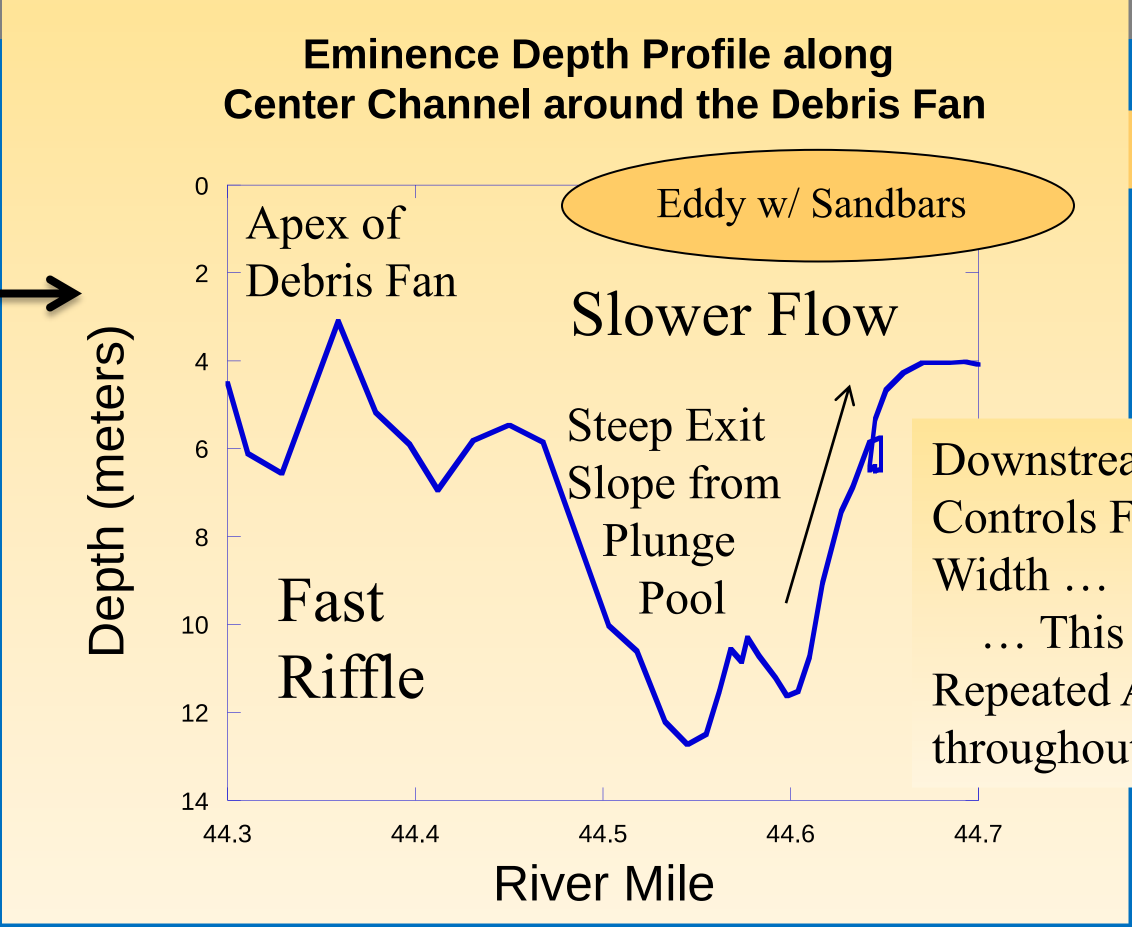
Debris Fans constrict flow at pinch points – flow quickly expands below – Creating Sand Traps – What about Depth?

Vertical Profile of the Part We Can't See

River Flow



∇ 8,000 cfs stage

Downstream Debris Fan Controls Flow & Channel Width …
… This Sequence is Repeated Again & Again throughout Grand Canyon

***Q:* Can Channel Processes Adjacent to Eddies Influence Sandbars?**

Q: What are "Nonperiodic Eddy Pulsations" & why do some sandbars suddenly disappear without warning?

(Rubin and McDonald, 1995)

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Sooner or Later – ALL Tributaries have their Day!

Mouth of “McDonald” Creek – 1890
Looking Downstream

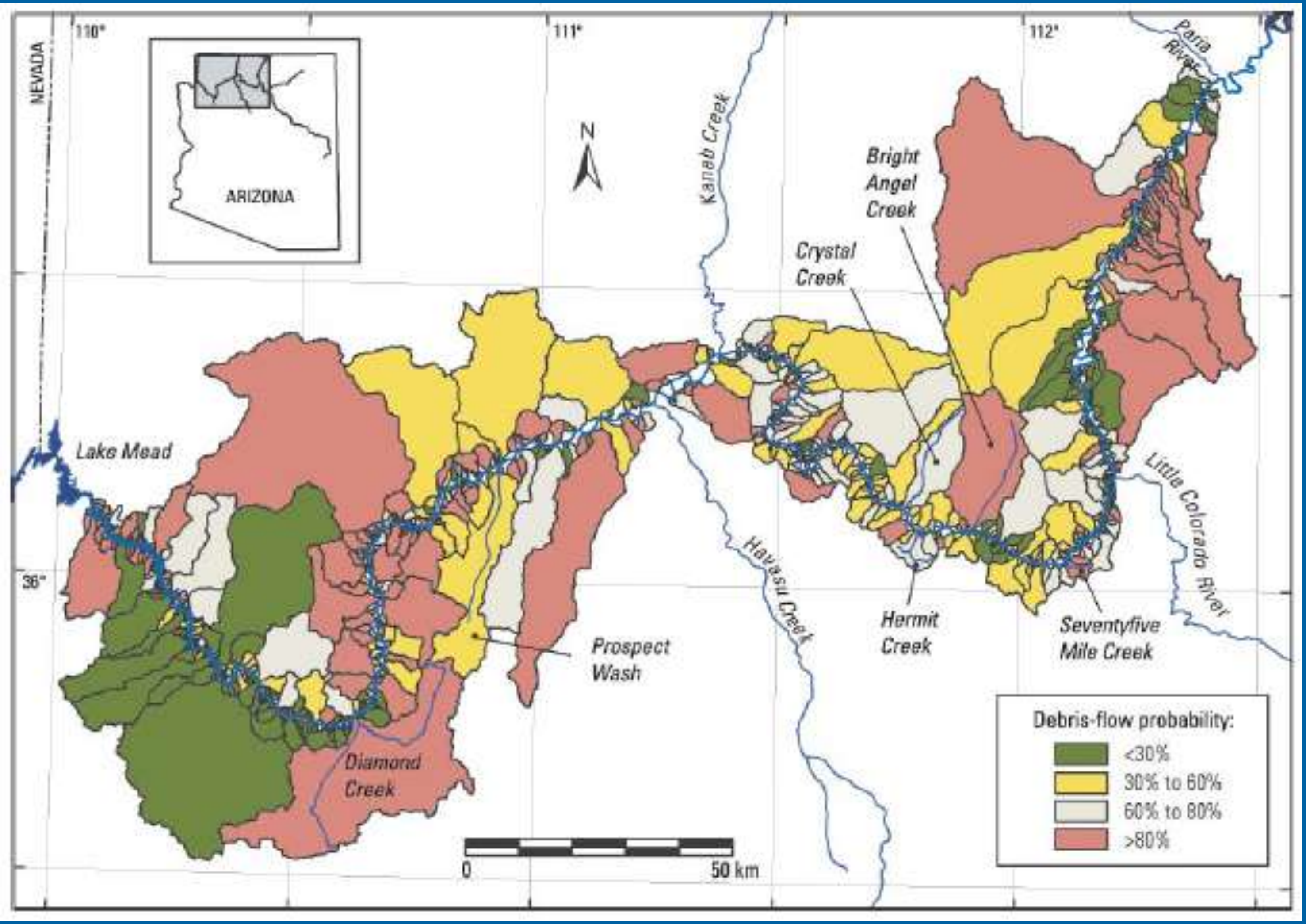
Original Photo:
Robert Brewster Stanton

USGS

Repeat View – Crystal Rapid – 1990
Showing influence of Dec. 1966 debris flow from Crystal Creek – geomorphic influence of gravel inputs is large and persistent under regulated river conditions

Match Photo:
T. Brownold

Debris Flow Probabilities vary throughout Canyon



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<u>Upper Marble Canyon</u> - has some of the highest debris-flow potential – as do the small basins in the lower Little Colorado River gorge (think – chub access to spawning habitat)

Presentation Outline

II- <u>Sediment Mass Balance</u> – two competing sediment budgets – but only one Canyon river

Sand vs. Gravel

Sediment Mass Balance – Two Budgets – One Canyon - *The Fate of Gravel & Sand Inputs*

GRAVEL Inputs(tributaries) – GRAVEL Export(mainstem) = GRAVEL ΔStorage(channel)

- Gravel – unlike sand, gravel tumbles along the bed and is not transported in suspension under typical releases from GCD
- Do Sandbars Contain Gravel? – studies show that sandbars coarsen upward, but do not contain gravel-sized sediments
- Fate of Gravel Inputs – high flows do rework new debris-fan & streamflow gravel deposits, but only to a limited extent
- Gravel - is aggrading tributary mouths/debris fans and likely are accumulating in deeper, slower areas of the channel between rapids – but apparently, not within eddies so far?

ΔStorage(gravel/channel) **POSITIVE** (as far as we know)

Sand vs. Gravel Inputs– What are their fates?

- **<u>Sand</u>** – [0.063 mm – 2 mm] comes mostly from younger & softer Mesozoic rocks higher in 2 large tributaries – Paria and Little Colorado River – outside Grand Canyon

- **<u>Gravel</u>** – [2 mm to car-size boulders] are delivered by 768 smaller basins draining older & harder Paleozoic rocks in Grand Canyon – frequent streamfloods & debris flows (less frequent)

<u>Is River "Sediment Supply" or "Transport" Limited</u>? – What grain sizes?

Q: Is Grand Canyon filling up with Gravel inputs? [YES - apparently]

Q: Will gravel fill the channel while eddy sandbars erode? [Unknown]

USGS *Q: Which size-class is most-supply limited below the Dam? [The Sand]*

What Do Tributary Gravel Deliveries Look Like? (Scary)

Deposits from Warm Springs Creek Debris Flow - 1965

Debris Flows - Occur throughout the Colorado River Basin – much less frequently than *streamflow* floods that also deliver gravel, but in more modest volumes/sizes

Photos courtesy of: Bruce Julian

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Sand & Gravel Inputs to Marble Canyon (From Paria to Little Colorado Rivers)

SAND INPUTS

Paria River Sand + Ungaged Sand Sources to Marble Canyon:

Recent Average ~ 700,000 – 800,000 metric tons/yr (last decade)

GRAVEL INPUTS

Ungaged GRAVEL inputs to Marble Canyon:

Perhaps ~ 600,000 metric tons/yr *(estimate from: Webb et al., 2000)*

Questions: We think we know where the sand goes (either into eddies or exported downstream), but where are those gravel inputs accumulating? What are possible long-term ecological implications for aggradation of the main channel (abiotic & biotic responses)?

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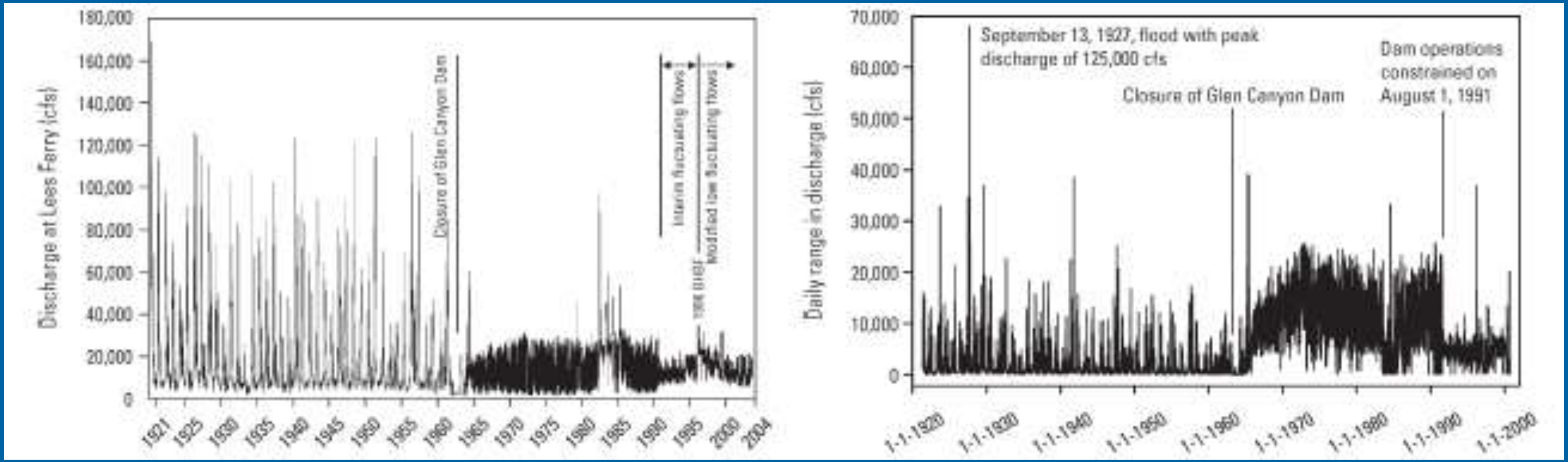
Presentation Outline



III - <u>GCD & flow of the Colorado River?</u> – the many challenges to sand conservation in the Canyon …

Highlights from: USGS Professional Paper 1677 (Topping et al., 2003)

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Δ 's In Flow & Influence on Suspended-Sediment Transport below GCD

<u>Key Controls on Sand Transport:</u> Recall that <u>*sand supply*</u> (only a fraction of what was formerly supplied) & <u>*sand grain size*</u> (very fine in our case) greatly influence suspended-sand transport /sand mass balance below Glen Canyon Dam

But, Flow REALLY Matters Too!

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How Has Flow in the Colorado River Changed? *… let us count the ways …*

A Review of USGS Professional Paper 2003-1677 (Topping et al., 2003)

Photograph courtesy of T. Ross, Bureau of Reclamation

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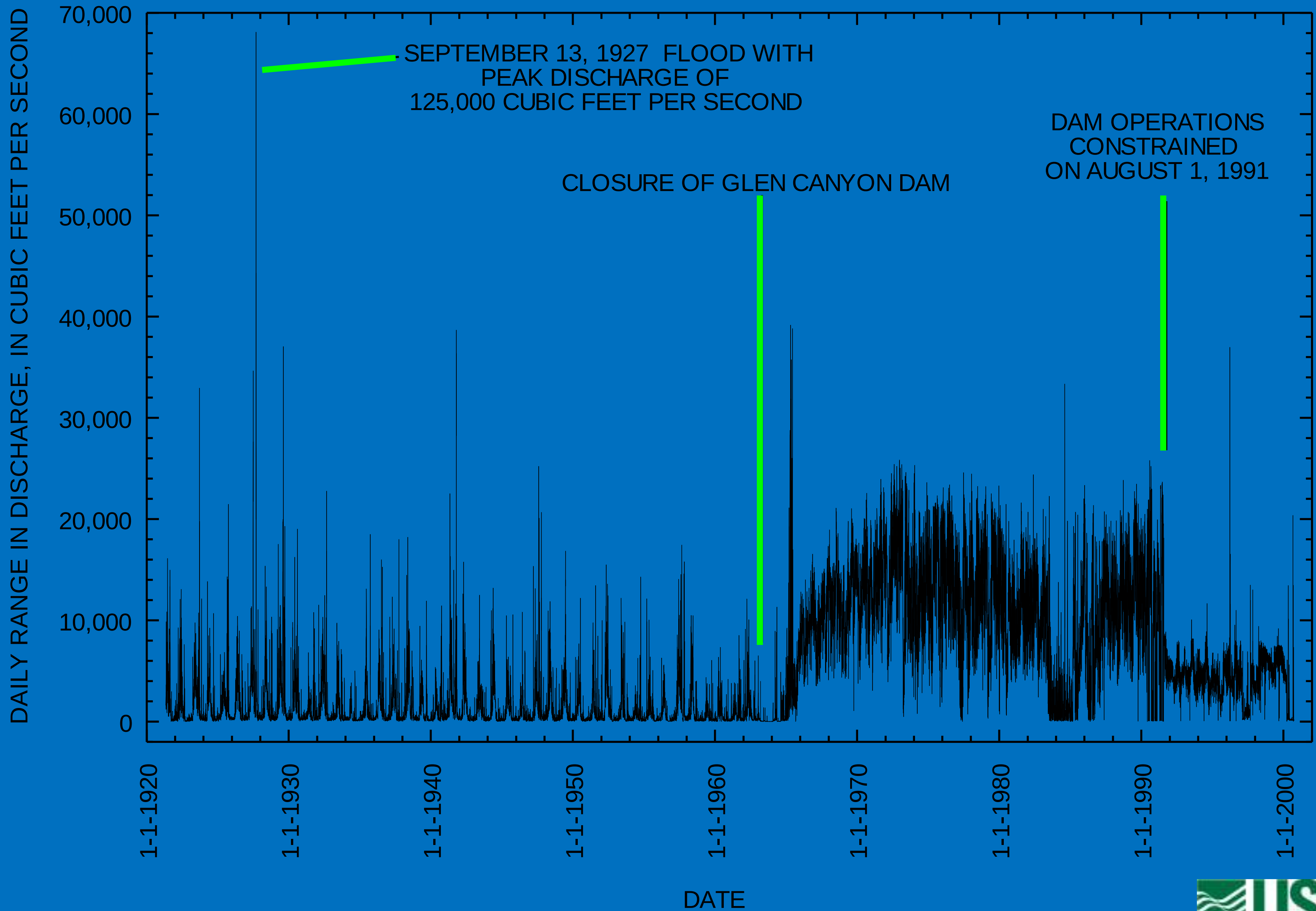
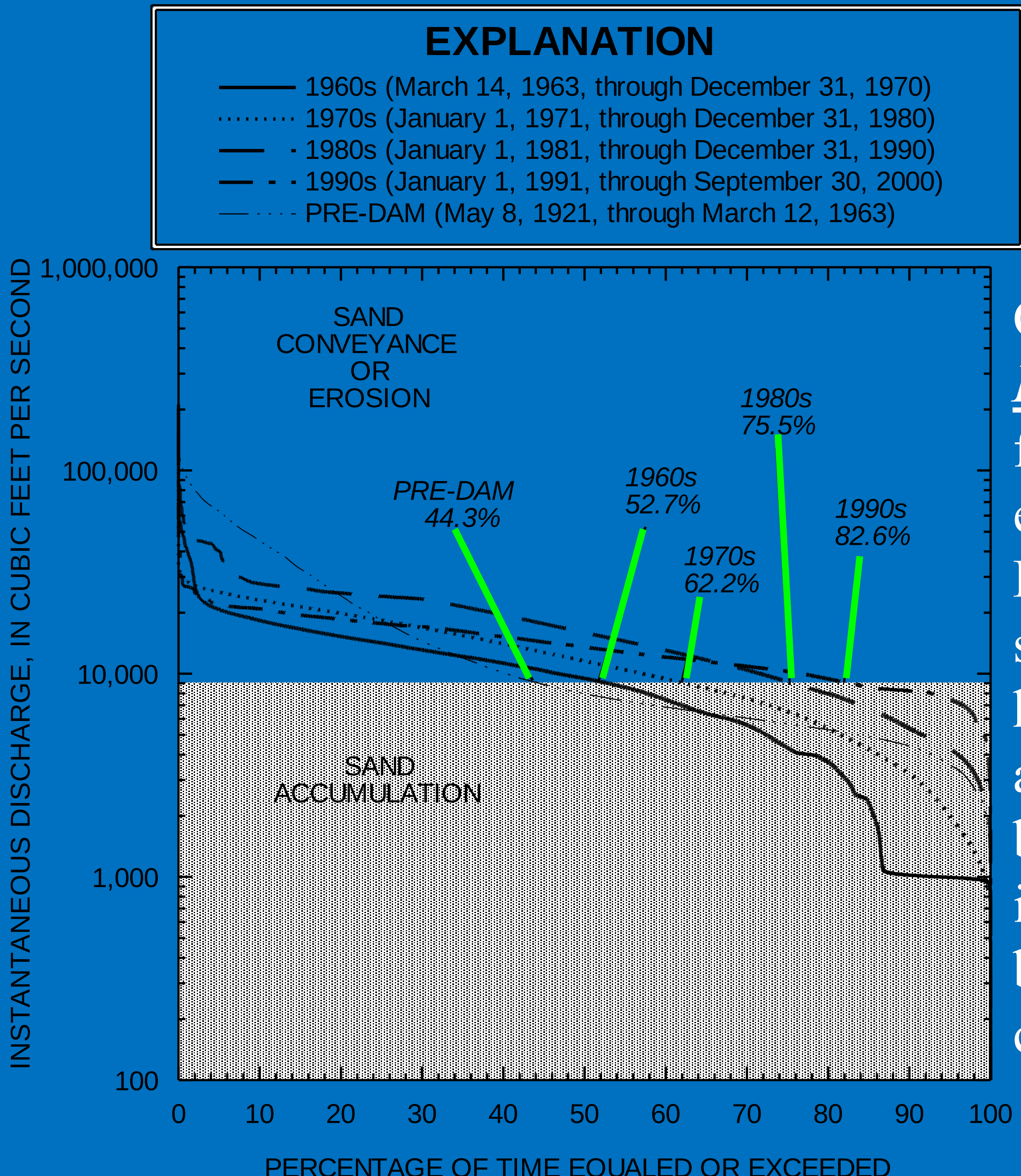
Challenges to Sand Management & Sandbar Conservation

We Know that River Flows Changed Because of GCD, ***But How So?***



(from Topping et al. 2003)



Over time, the ***Duration*** of flows that export our Paria River sand inputs has gone up and up - even being increased by 1996 ROD constraints!

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Median Flow & Daily Range

- **Median Discharge – was nearly doubled by regulation – increasing from 7,980 ft^3/s pre-dam to 13,500 ft^3/s in the 1990s**

- **Pre-dam base flows largely eliminated - pre-dam minimum discharge = 483 ft^3/s; pre-dam discharges < 5,000 ft^3/s 32.7% of the time**

- **Median daily range in discharge - has increased by a factor of 15.8 relative to pre-dam - post-dam median daily range (8,580 ft^3/s) exceeds pre-dam median discharge (7,980 ft^3/s)**

- **Post-dam daily fluctuations - exceed pre-dam fluctuations - except during 0.1% of all pre-dam days**

- **Flows conducive to sand export – (flows above 9,000 ft^3/s) were progressively increased – from 52.7% of the time in 1960s to 82.6% of the time in the 1990s – *Pre-dam 9,000 ft^3/s was only exceeded 44.3% of the time***

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(from Topping et al. 2003)

Summary of Knowledge

- Substantial natural variability existed in discharge and in the daily range in discharge over decadal timescales prior to construction of the dam

- Changes imposed on the hydrology by dam operations exceed anything in the quasi-natural pre-dam period of record; seasonality removed from both discharge and the daily range in discharge

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(from Topping et al. 2003)

Timing of High Flows Matters Too!

The highest annual flows released from GCD now mostly coincide with the late summer sediment input season of the Paria River (July – September)

While low flows that formerly retained sand inputs from summer through fall & winter in pre-dam time are now replaced with a 2nd period of high fluctuating releases in winter months

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What About Water Temperature?

Shift from Warm Water during Summer Sediment Input Season (85° F) to Cold Water (47° F) now released from the dam also enhances suspended transport & export of fine sand (*viscosity effects on particle settling*)

Current thermal regime also favors export over retention of Paria River sand in the main channel

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Nearly everything that can promote sand export – IS!

Q: "So, Why Do Sandbars Erode after HFEs?"

A: "They are exposed to higher, clearwater fluctuating flows – most of the time."

~50 to 90% of the sand in Marble Canyon is stored in eddies. About 90% of the sand in eddies is stored below the stage elevation reached by a flow of 8,000 ft^3/s (Hazel et al., 2006, *J. Geophys. Res.*, 11)

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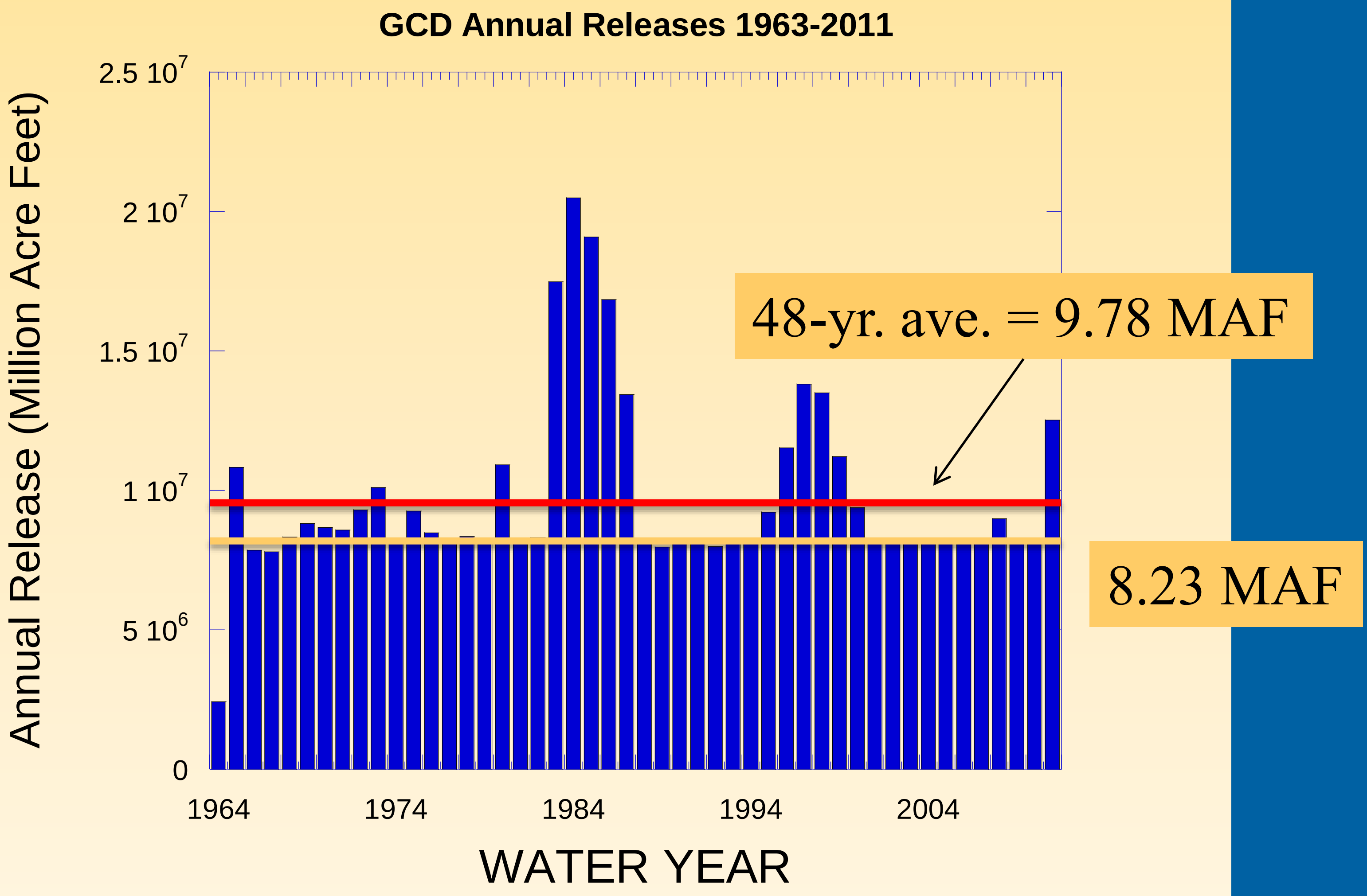
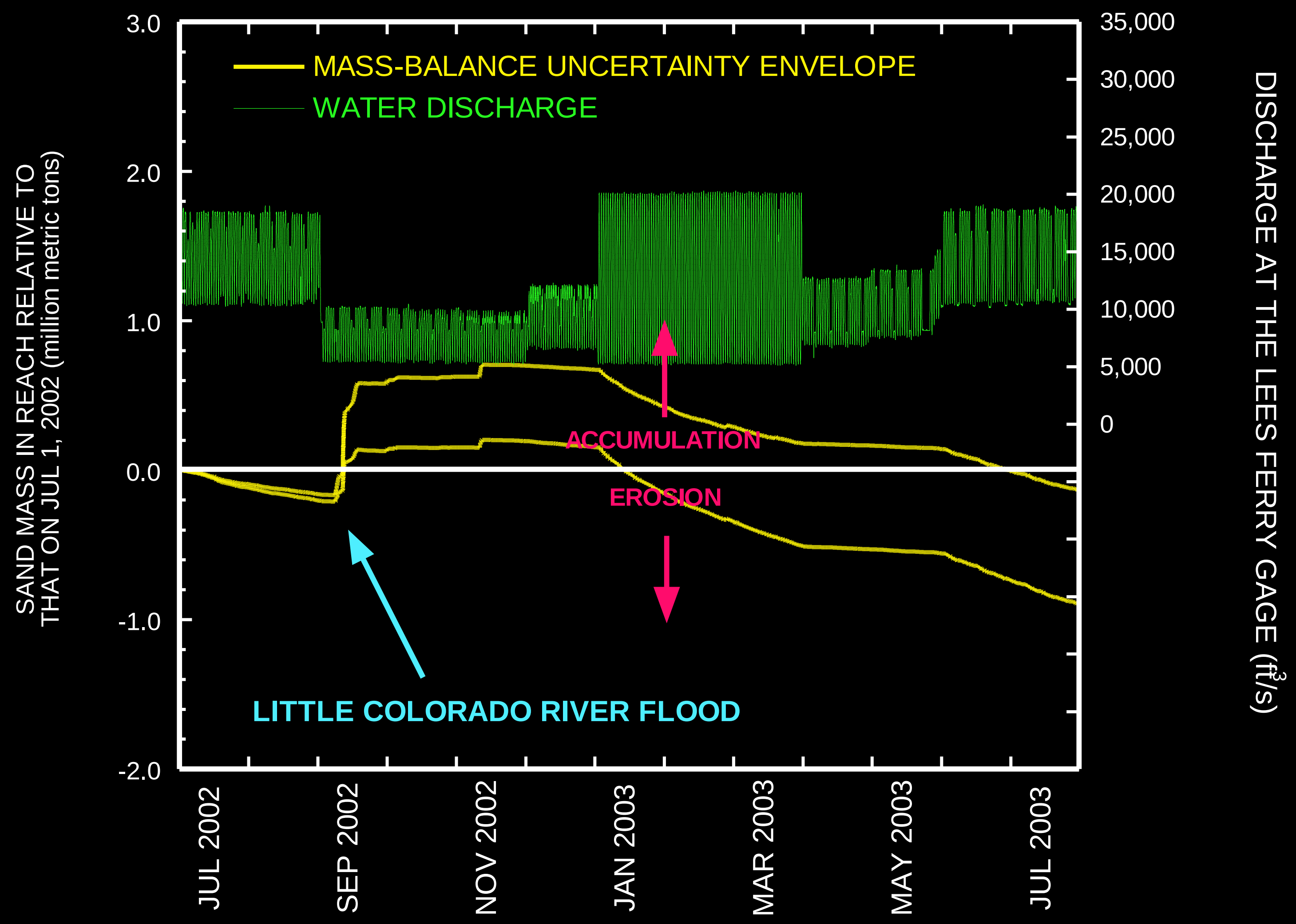
Data: courtesy of R. Clayton, Bureau of Reclamation



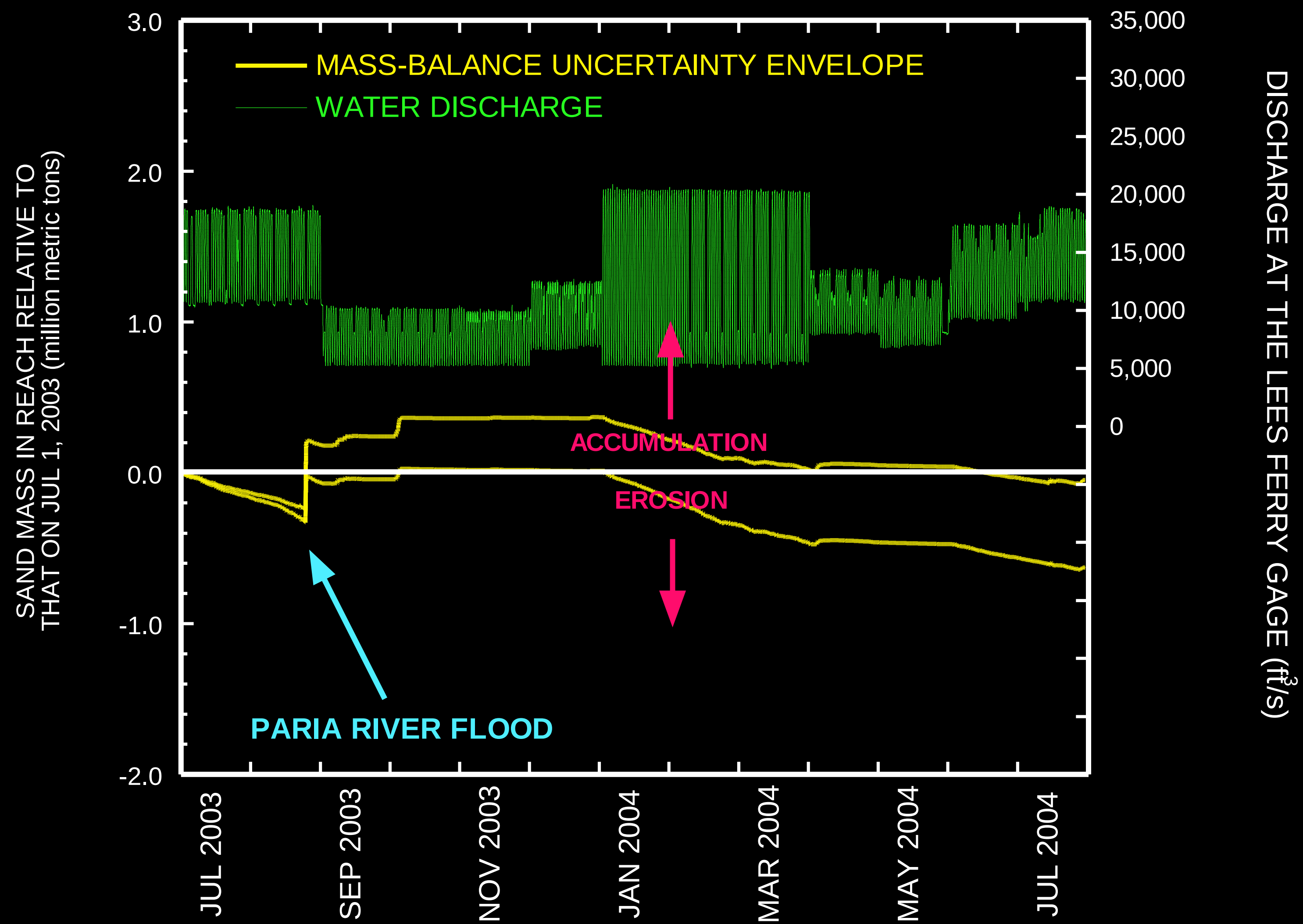
It has been estimated that under 8.23 MAF releases w/ steady flows & annual controlled floods that sandbars might be sustainably rebuilt (Wright et al. 2008, *GSA Today*)

SEDIMENT-YEAR 2003 MASS-BALANCE SAND BUDGET BETWEEN LEES FERRY AND THE GRAND CANYON GAGE



It seems to be the GCD releases above ~ 10,000 cfs
… As suggested by Topping et al. (2000a,b & 2003)

SEDIMENT-YEAR 2004 MASS-BALANCE SAND BUDGET BETWEEN LEES FERRY AND THE GRAND CANYON GAGE



This is obvious in back-to-back 8.23 MAF years (2003-04)
When "experimental" fluctuations (5-20 kcfs) occurred for trout suppression

Implications

of

Evolving Channel-Bed Conditions/Geometry

???

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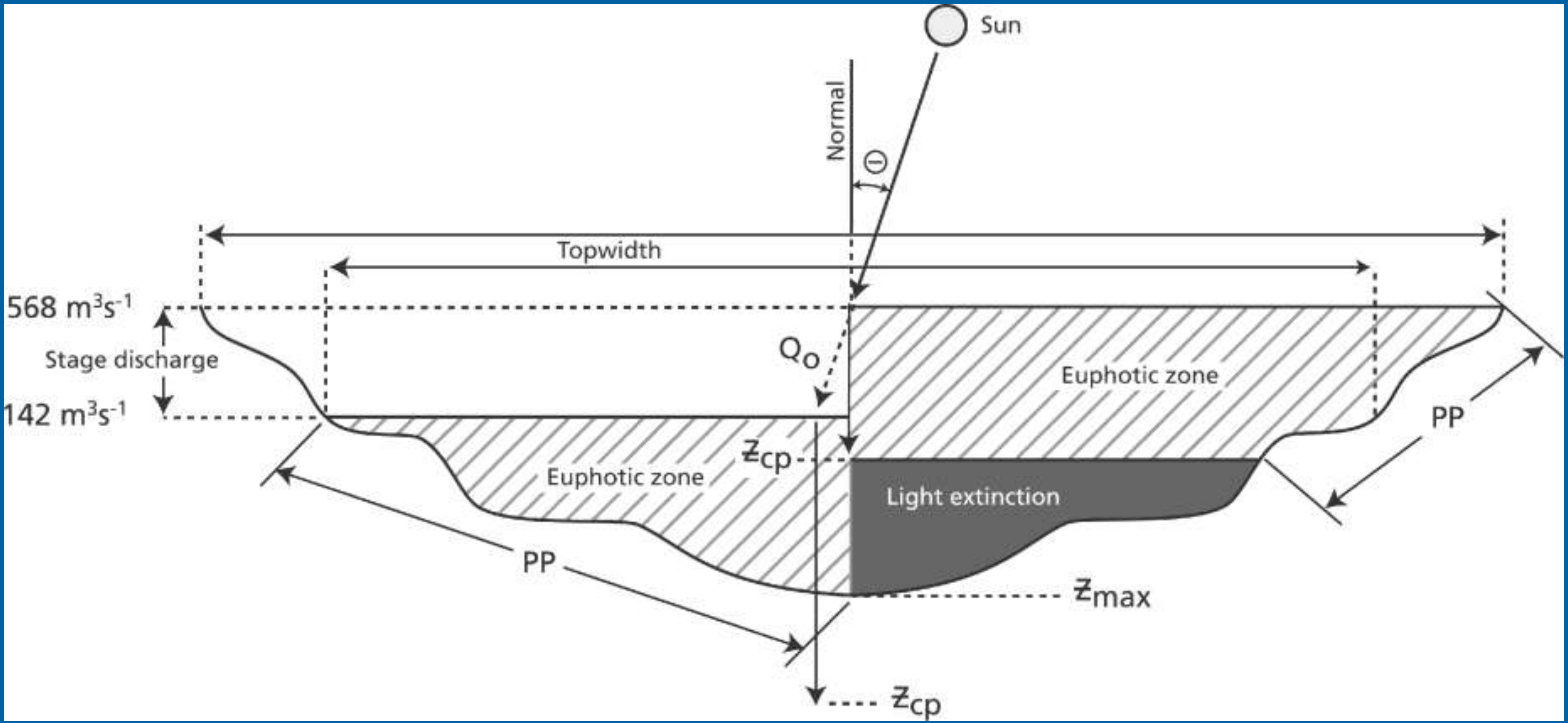
Aquatic Food Production & the Bed of the Colorado River Channel



Water Depth Limits Light Penetration to the Bed (primary & secondary production of Benthic Organisms - from Yard, 2003)

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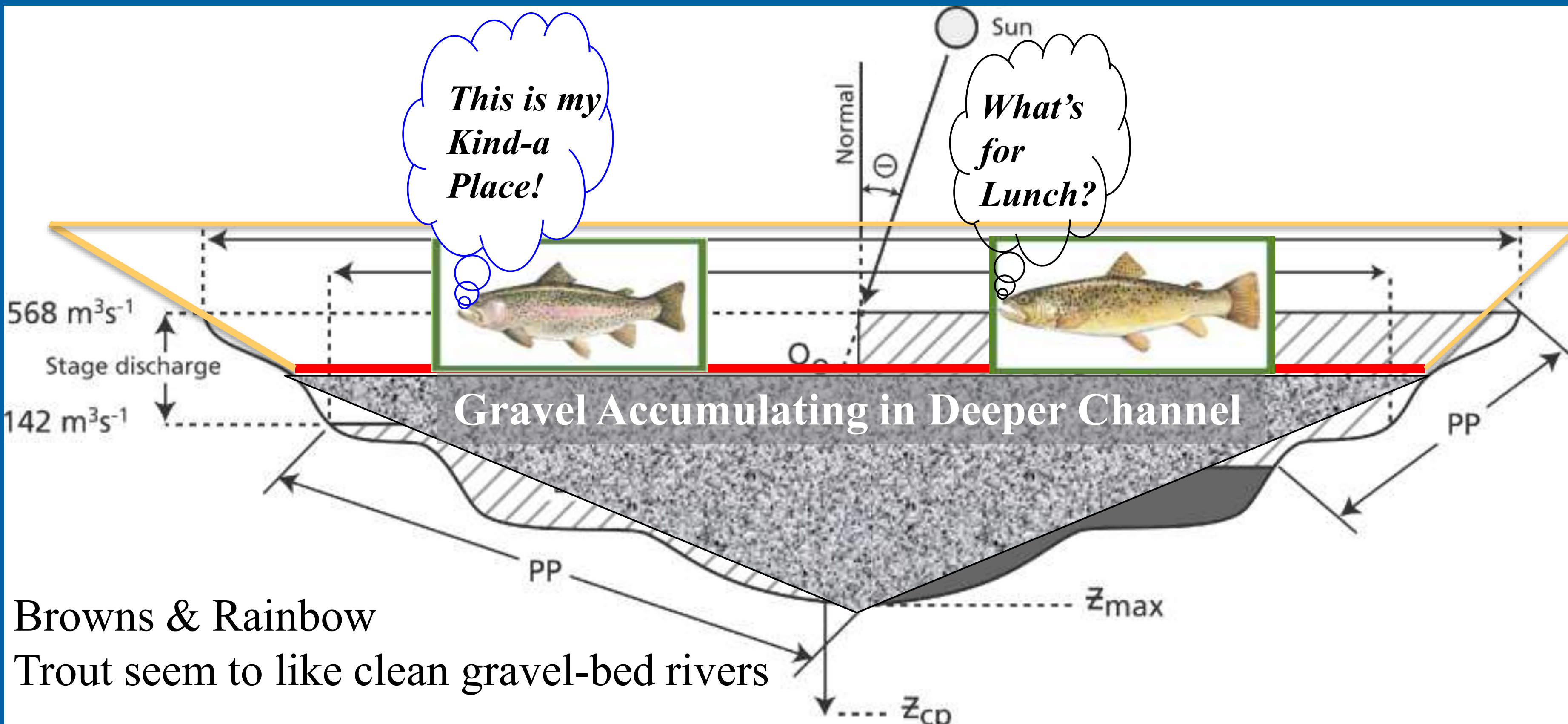
Ongoing Gravel Inputs – Influence on Channel Geometry?



<u>If Depths Become Shallower</u> - Will light penetration to the bed increase food production? What would happen to flow velocities in the channel and the potential for sand storage in eddies under aggraded conditions?

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Implications of gravel inputs, high flows & changes in food availability on native & nonnative fishes?

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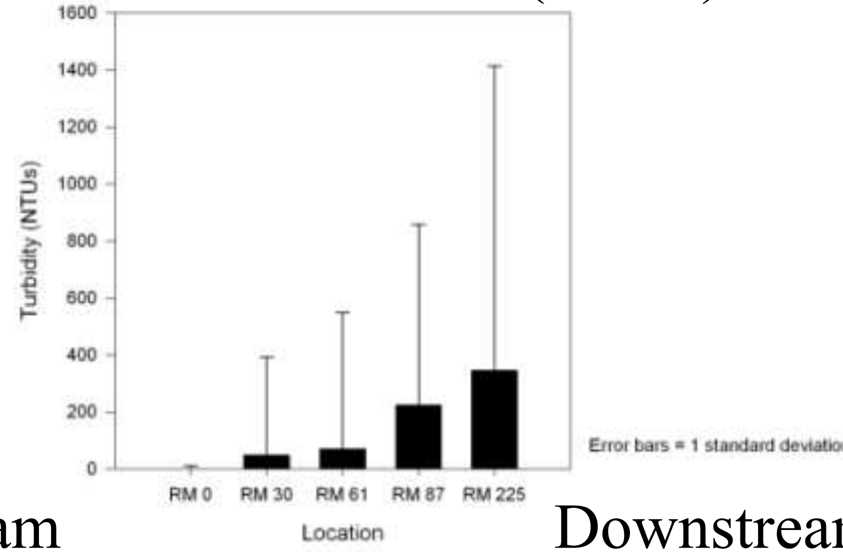
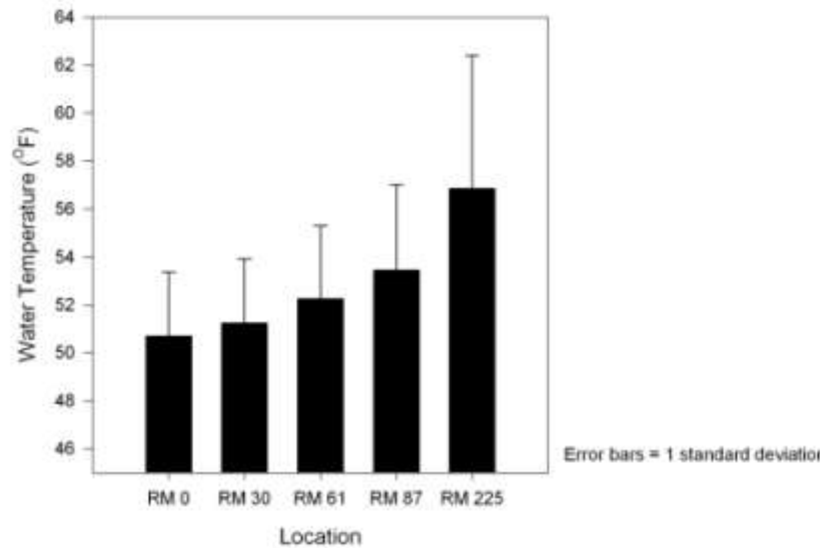
AVE. TURBIDITY (NTUs)

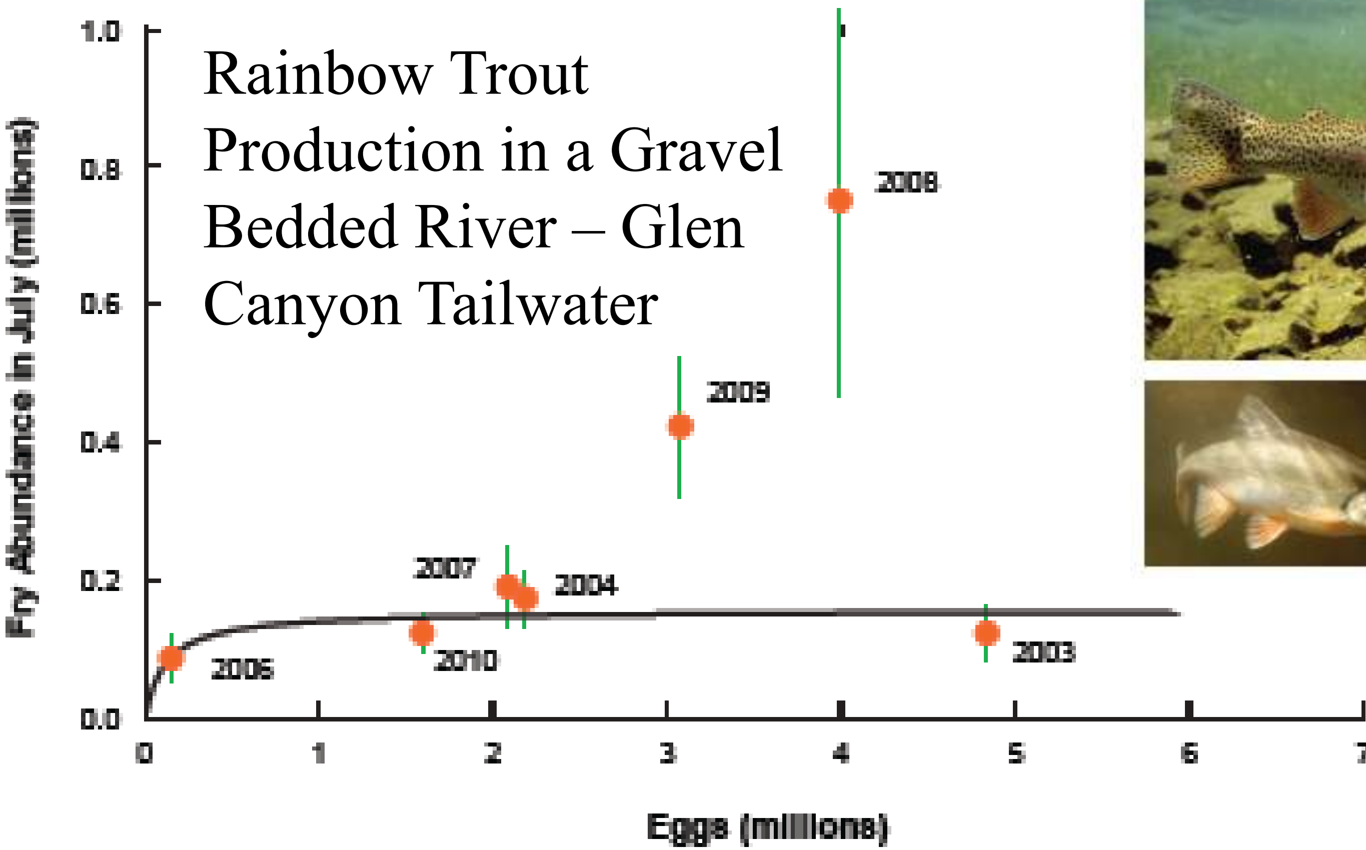


Upstream

Downstream



AVE. TEMPERATURE (degrees F)



The relation between the number of viable rainbow trout eggs deposited in the Lees Ferry reach and the resulting population size of fry in mid-July for the years 2003–10 (no data for 2005). The thick black curve shows the best-fit relation between viable eggs and fry using data from all years except those affected by the March 2008 high-flow experiment (2008 and 2009), when survival was unusually high. The flat relation indicates that the survival rate from egg to fry stage increases with reduced numbers of eggs, a compensatory effect that mininizes the effect of egg losses on fry abundance. The green vertical lines show the 95-percent confidence limits of fry abundance estimates. (From Korman and others, in press).

Are tailwater conditions that make Glen Canyon ideal for Trout extending <u>downstream</u> into Marble Canyon?

from Korman et al. 2011, *TAFS*

Bonus Slides

Studying Future Sediment Responses

Key Question: Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?

Answer, so far: (after 3 HFEs): "Perhaps"

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From Chapter 5, Wright and Kennedy, 2011

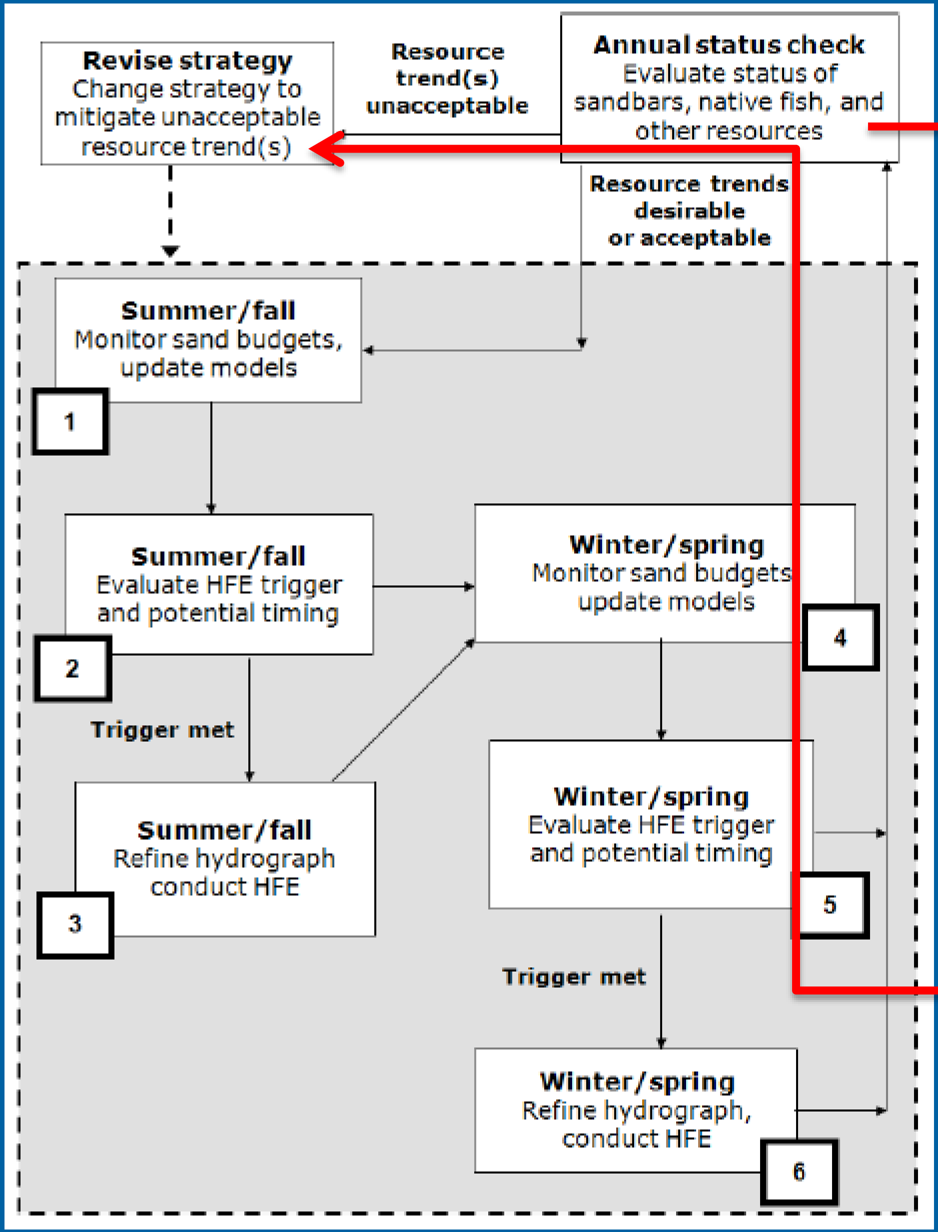

Figure 7. Flow chart illustrating the decision-making process for a science-based experimental strategy for tributary sand-input triggered HFEs with two sand-budget accounting periods and two HFE windows per year. Each box and decision point is described in detail in the text.

ADDRESSING UNCERTAINTY

If monitoring under the current HFE Protocol triggering strategy indicates that sandbars continue to erode or cannot be rebuilt and sustained at a desired level

then,

decision makers may choose other experimental options, such as further constraining dam releases, augmenting sand supply to Grand Canyon from sources in Lake Powell, or both …

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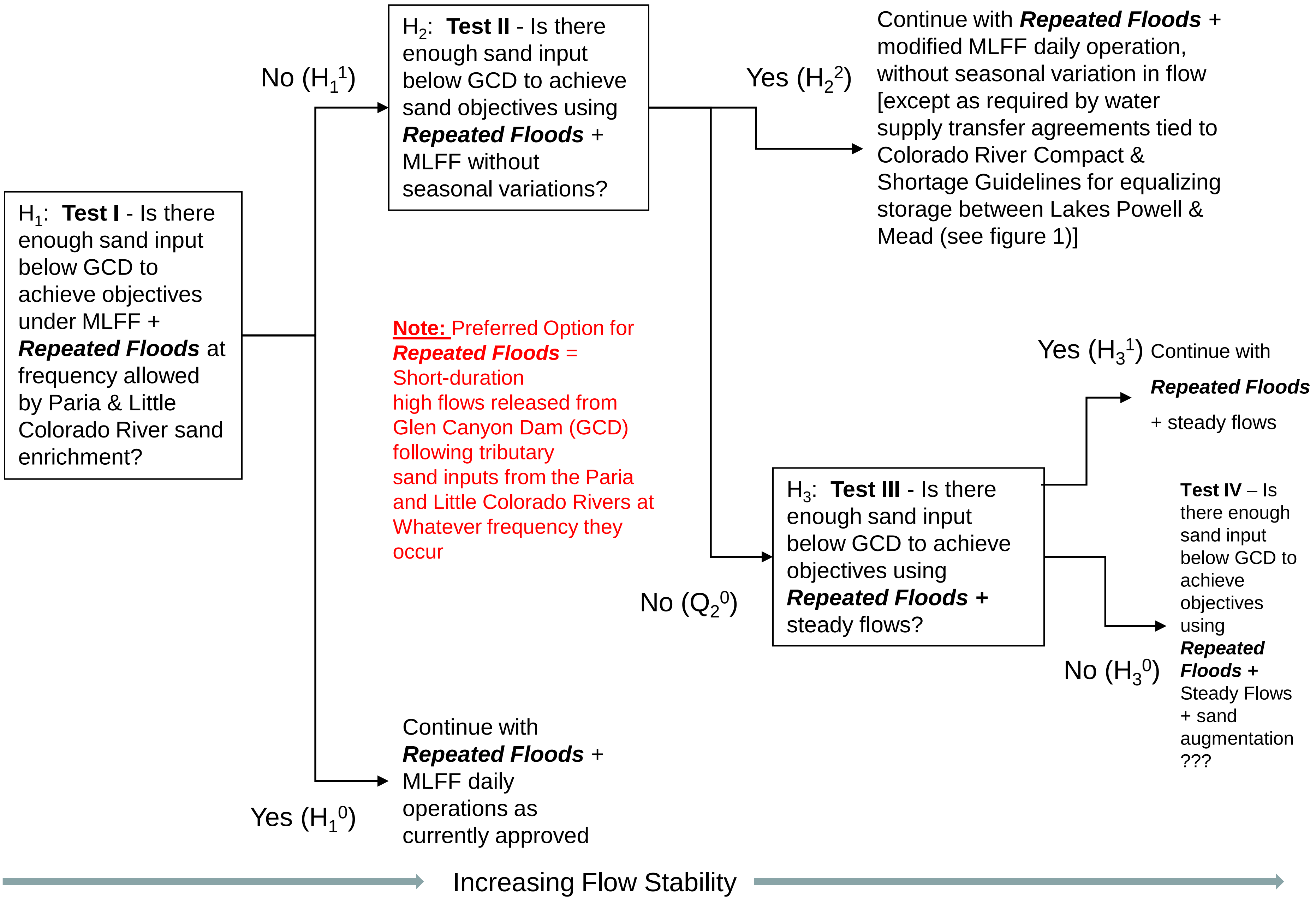
A Strategy for Sediment Experiment

"*Adaptive Strategy*"
Evaluating Use of Repeated Controlled Floods to Rebuild Sandbars below Glen Canyon Dam



Why Not Try to Capitalize on Mother Nature's Bounty?

Matching Up with LCR Floods

Vol. 9, No. 4 April 1999

GSA TODAY

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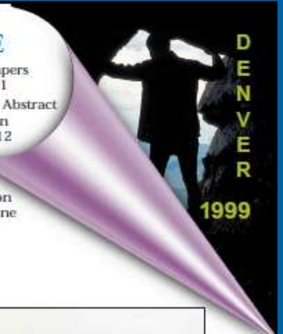

Floods and Sandbars in the Grand Canyon

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Luna B. Leopold, 400 Vermont Avenue, Berkeley, CA 94707

ABSTRACT

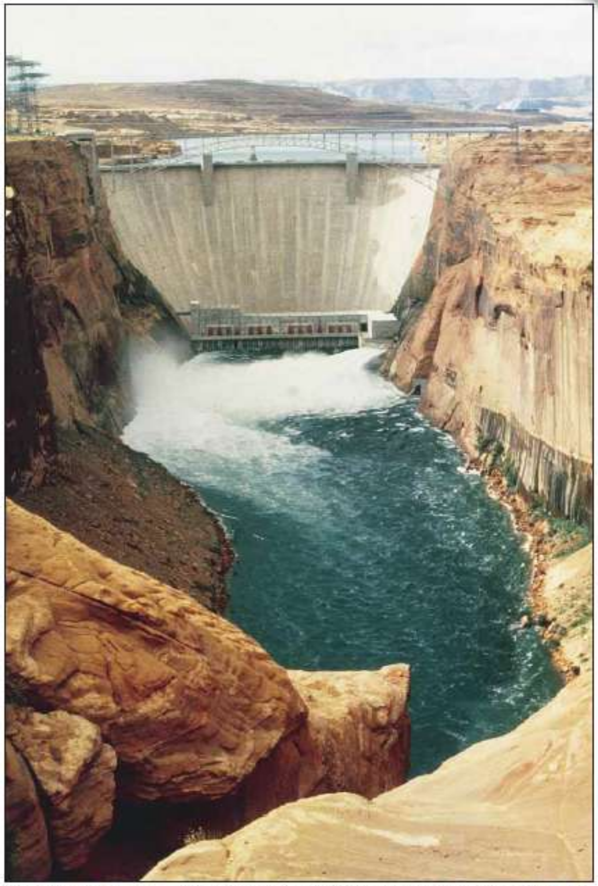
Erosion of sandbars and beaches in the Grand Canyon National Park downstream from Glen Canyon Dam has become a major problem that needs to be addressed. Geomorphic and geologic mapping provide a link between sandbar elevations and discharge measurements. This link allows an estimate of discharges that will deposit sand far enough above normal high water to prevent frequent depletions by erosion. The sand is needed to protect habitats and archaeological sites and to maintain beaches used by recreationists. It is proposed that when the Little Colorado is in flood, discharge at Glen Canyon Dam be increased to bring the total discharge to the desired high value. Analysis of the flow records show that such opportunities are presented on the average once in eight years, suggesting that the proposal has a reasonable chance of success.

INTRODUCTION

The Colorado River in the Grand Canyon section in Arizona once fluctuated greatly in its flow. Year-to-year and season-to-season variability was large. Peak discharges ranged from 300 000 cfs (cubic feet per second) to 19 200 cfs, a difference of 16 times. The amount of sediment transported as suspended load was very large. Measurements carried out at the Grand Canyon for the period December 1940 to June 1941 show that, at 50 000 cfs, about 2 000 000 tons were moved per day during the rising stage of the flood,[1] and 500 000 tons during the falling stage, whereas almost 5 000 000 tons per day were moved during the peak of the flood

Grand Canyon *continued on p. 2*

[1]Sediment transported during the rising stage of a flood is much greater than that transported during the falling stage (Leopold and Maddock, 1953).



Glen Canyon Dam at high discharge during the June 1983 flood. The dam is 710 ft (216 m) high. The four jets of water issuing from near the lower right corner of the dam are from the outlet works. Releases from the right spillway are hidden by the cloud of mist and spray near the lower left corner of the dam. The left spillway, whose exit is visible a short distance downstream from the outlet-work jets, was inactive when the photo was taken. Discharge from the powerplant is below river level and not visible. Photo courtesy of David L. Wegner